

HNCO enhancement by shocks in the L1157 molecular outflow

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ABSTRACT

Context. The isocyanic acid (HNCO) presents an extended distribution in the centers of the Milky Way and the spiral galaxy IC342. Based on the morphology of the emission and the HNCO abundance with respect to H₂, several authors made the hypothesis that HNCO could be a good tracer of interstellar shocks.

Aims. Here we test this hypothesis by observing a well-known Galactic source where the chemistry is dominated by shocks.

Methods. We have observed several transitions of HNCO towards L1157-mm and two positions (B1 and B2) in the blue lobe of the molecular outflow.

Results. The HNCO line profiles exhibit the same characteristics of other well-known shock tracers like CH₃OH, H₂CO, SO or SO₂. HNCO, together with SO₂ and OCS, are the only three molecules detected so far whose emission is much more intense in B2 than in B1, making these species valuable probes of chemical differences along the outflow. The HNCO abundance with respect to H₂ is 0.4-1.8 10⁻⁸ in B1 and 0.3-1 10⁻⁷ in B2. These abundances are the highest ever measured, and imply an increment with respect to L1157-mm of a factor up to 83, demonstrating that this molecule is actually a good shock tracer.

Conclusions. Our results probe that shocks can actually produce the HNCO abundance measured in galactic nuclei and even higher ones. We propose that the gas phase abundance of HNCO is due both to grain mantles erosion by the shock waves and by neutral-neutral reactions in gas phase involving CN and O₂. The observed anticorrelation of CN and HNCO fluxes supports this scenario. The observed similarities of the HNCO emission and the sulfured molecules may arise due to formation pathways involving also O₂.

Key words. ISM: individual (L1157) – ISM: jets and outflows – ISM: molecules – stars: formation – shock waves

1. Introduction

Interstellar *isocyanic acid* (HNCO) was first detected towards Sgr B2 (Snyder & Buhl 1972; Churchwell et al. 1986; Kuan & Snyder 1996). Since the first detection in this source, the molecule has been observed in other hot cores around massive (Blake et al. 1987; MacDonald et al. 1996) and low mass protostars (van Dishoeck et al. 1995; Bisschop et al. 2008). It has also been detected in translucent clouds (Turner et al. 1999) and in the dense regions of Galactic molecular clouds (Jackson et al. 1984; Zinchenko et al. 2000), including those in the Galactic center (Hüttemeister 1993; Lindqvist et al. 1995; Dahmen et al. 1997; Rizzo et al. 2000; Minh et al. 2005; Martín et al. 2008). HNCO has also been detected in some extragalactic sources (Nguyen-Q-Rieu et al. 1991; Meier & Turner 2005; Martín et al. 2009). The isotopologue HCNO (fulminic acid) has recently been detected by Marcelino et al. (2009).

The emission in HNCO lines with $K_{-1} = 0$ ¹ is clearly extended in the two Galactic nuclei where it has been

mapped: IC342 (Meier & Turner 2005) and the Milky Way (Lindqvist et al. 1995; Dahmen et al. 1997). In the Galactic center the spatial distribution of the HNCO emission is different from that of most other tracers. In particular, there is a HNCO peak without an associated CO peak at Galactic longitude $l = 1.65^\circ$ (Dahmen et al. 1997). This very special distribution suggests that HNCO can be an important tracer of some physical processes that are not well revealed by other molecules. It is possible that the molecule is tracing shocks, which are thought to take place at this Galactic longitude due to the gas dynamics in the barred potential of the Milky Way (Rodríguez-Fernandez & Combes 2008). Indeed, in the Galactic center, the highest gas phase abundances of SiO (a well-known shock tracer) are measured in this region (Hüttemeister et al. 1998; Rodríguez-Fernandez et al. 2006). Also on the basis of a special morphology of the HNCO emission in Sgr B2, Minh & Irvine (2006) suggested that HNCO is enhanced by shocks. Regarding IC342, the HNCO emission resembles that of CH₃OH. In particular, HNCO is detected not only in the nuclear ring but also in the inner spiral arms or *dustlanes*. Since the dustlanes are thought to be the locus of strong shocks in barred galaxies (see for instance Rodriguez-Fernandez & Combes 2008, and references therein), Meier & Turner (2005) suggested that HNCO, as CH₃OH, could trace large scale shocks.

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¹ HNCO is a planar, nearly linear, slightly asymmetric prolate rotor. The notation for a given level is $J_{K_{-1}K_1}$. The $K_{-1} = 0$ are usually excited thermally, while the excited K ladders ($K_{-1} > 0$) are probably excited by FIR radiation (Churchwell et al. 1986).

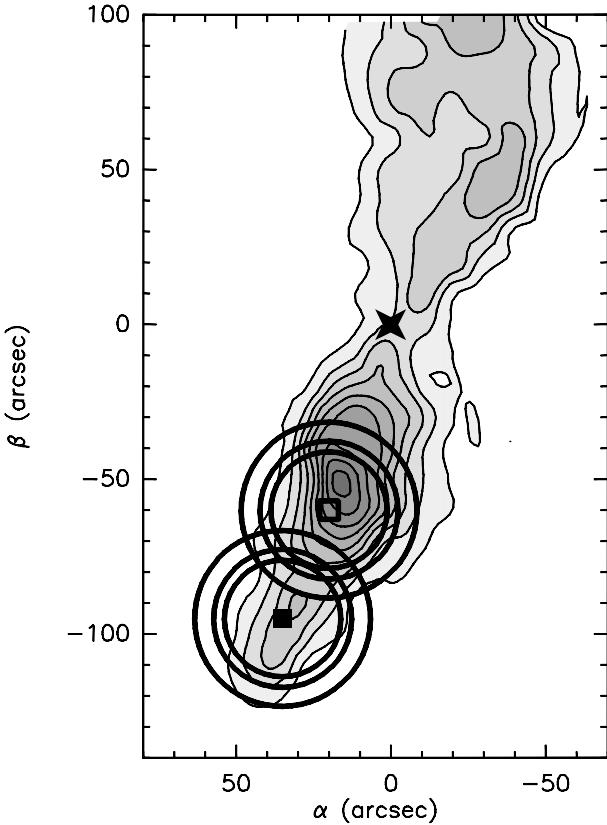


Fig. 1. Integrated CO(2-1) emission from the L1157 outflow (Bachiller et al. 2001). We show the position of L1157-mm (star), B1 (empty square) and B2 (filled square). B1 and B2 are the positions of the shocks as traced, for instance, by SiO(3-2) (see Fig. 6 of Bachiller et al. 2001). The CO emission peaks behind the actual positions of the shocks. The different circles represent the half maximum contours of the IRAM 30m beam at the frequencies of the lines discussed in this paper (see Table 1).

Nevertheless, the hypothesis that HNCO is a good shock tracer at the scale of galaxies still needs to be probed since the HNCO emission has never been studied in well-known Galactic templates of interstellar shocks. In order to better understand the excitation and the chemistry of this promising molecule, we have observed the protostar L1157 and its associated molecular outflow. This outflow presents the morphological signature of shocks (Gueth et al. 1998; Codella et al. 2009) and it is frequently used to benchmark numerical models of shocks (Gusdorf et al. 2008a,b). L1157 is the best example of “chemically active outflow” (Bachiller et al. 2001) and a template of shock chemistry, since many species exhibit large abundance increments with respect to the protostar (Bachiller & Perez Gutierrez 1997). Therefore, it is a source of choice to characterize the emission of a given molecule in a shocked environment (see for instance Bachiller & Perez Gutierrez 1997; Bachiller et al. 2001; Benedettini et al. 2007; Arce et al. 2008; Codella et al. 2009).

Table 1. Observational parameters.

Line	ν^a GHz	B_{eff}^b	F_{eff}^c	FWHM ^d arcsec	T_{sys}^e K	rms mK
4-3 ^f	87.925	0.78	0.95	28.4	100	12-18
5-4 ^g	109.905	0.75	0.95	22.3	180	16-19
6-5 ^h	131.885	0.69	0.93	18.8	215	28-34

Notes. ^(a) Frequency ^(b) Beam efficiency ^(c) Forward efficiency ^(d) Full width at half maximum of the telescope main beam ^(e) System temperature ^(f) $4_{0,4} - 3_{0,3}$ ^(g) $5_{0,5} - 4_{0,4}$ ^(h) $6_{0,6} - 5_{0,5}$

2. Observations

We have observed three lines of the $K_{-1} = 0$ ladder of HNCO towards the two main shocks in the southern lobe of the L1157 molecular outflow: the B1 and B2 positions of Bachiller & Perez Gutierrez (1997). In addition, we have observed as reference the continuum source L1157-mm (the protostar). The equatorial coordinates of L1157-mm are RA=20^h39^m06.19^s Dec=68°02'15.9", (J2000). The offsets of B1 and B2 with respect to L1157-mm are (20", -60") and (35", -95"), respectively.

The observations were done with the IRAM 30m telescope in Pico Veleta in July 2007. The line quantum numbers, frequencies and the telescope parameters are listed in Table 1. As backends we used the 100 KHz filterbank and the VESPA autocorrelator with a channel resolution of 20-40 MHz, which allows to study in detail the line wings. The observations were carried out in position switching mode with the OFF position located 24' NE from L1157-mm. Typical system temperatures and rms noise of the spectra are given in Table 1.

Table 2 gives the integrated flux of the different lines computed from spectra in T_{mb} units (forward and beam efficiencies are given in Table 1). The uncertainties in the calibration of the IRAM 30m telescope are within 10 % at the frequency of the lines discussed here (Mauersberger et al. 1989).

3. Results

3.1. Line profiles: differences between the observed positions

Figure 2 shows the spectra. The $4_{04} - 3_{03}$ and $5_{05} - 4_{04}$ lines have been detected in all the positions. In addition the $6_{06} - 5_{05}$ line has also been detected toward L1157-mm. The lines are narrow towards L1157-mm (linewidths of 0.7-0.9 km s⁻¹) but the linewidth increases by more than a factor of 3 towards the B1 and B2 positions. In particular, they show a prominent blue-wing towards B1.

Figure 3 shows a comparison of the HNCO ($5_{05} - 4_{04}$) line profile measured towards the three observed positions and the spectra of other molecules observed by Bachiller & Perez Gutierrez (1997). The line profiles are in overall good agreement with the other molecules. In particular, the HNCO profiles are very similar to those of CH₃OH, H₂CO, SO and SO₂, which are all shock tracers whose abundance has increased by more than a factor of 10 in the shocked gas with respect to the quiescent gas in L1157-mm. The HNCO line wings are narrower than SiO lines, in agreement with the findings of Zinchenko et al. (2000) in Galactic dense cores, but the SiO line profiles

are specially broad in the L1157 molecular outflow, being broader than those of all the other molecules as well.

As discussed by Bachiller & Perez Gutierrez (1997), most of the molecules exhibit lines with similar intensity in B2 and in B1. The exceptions are CN, which is very intense towards B1 but it is not detected towards B2, and the sulfur-bearing molecules SO₂ and OCS, whose lines are much more intense in B2 than in B1. It is interesting to point out that HNCO, whose lines are a factor of 2 more intense in B2 than in B1, is indeed the only non sulfur-bearing molecule showing this behavior.

3.2. Enhanced HNCO abundances in the shocked gas

The critical density of the HNCO transitions discussed here is high (5×10^5 – 10^6 cm⁻³; derived using the collisional coefficients in the LAMDA database for temperatures from 20 K to 320 K, Schöier et al. 2005). Therefore, it is likely that most of the emission comes from dense and small clumps as those found in B1 with the IRAM Plateau de Bure interferometer (Benedettini et al. 2007; Codella et al. 2009). For instance, the angular size of the CH₃OH clumps is 10''. However, without high angular resolution observations it is difficult to assign a very precise value to the size of the source emitting in HNCO. Therefore, all the following results have been obtained in two limiting cases: first, assuming that the size of the emitting region is 10'' and computing source brightness temperatures taking into account the corresponding beam filling factor. Second, assuming that the emitting region fills the primary beam of the telescope, and thus using T_{mb} temperatures.

3.2.1. LTE analysis

We have computed HNCO column densities assuming optically thin emission and LTE excitation. We have computed excitation temperatures from the 5₀₅ and 4₀₄ populations (T_{ex}^{54}) and from the 6₀₆ and 4₀₄ populations (T_{ex}^{64}). The temperatures T_{ex}^{64} are very low (5–6 K for mm and < 6 K for B1 and B2). The excitation temperature T_{ex}^{54} varies from 8 to 11 K for L1157-mm (depending on the assumptions on the source size), while it varies from 9 to 19 K in B1 and B2 (see Table 3). In order to study with great precision the HNCO excitation more than three transitions would be needed. Here, in order to obtain a conservative estimation of the total column density of HNCO we have extrapolated the population in the 5₀₅ and 4₀₄ levels using the T_{ex}^{54} . Of course, the total HNCO column density would be higher if the excitation temperature is actually lower. Using T_{ex}^{54} and assuming LTE excitation, the total HNCO column densities are 0.2–0.8, 1–1.9 and 1.5–3.8 (in units of 10^{13} cm⁻²) for mm, B1, and B2, respectively. Since the excitation is similar in B1 and B2, the highest line intensities measured towards B2 translate into larger column densities, in contrast to the CO column density which is a factor of 2 lower in B2 (Bachiller & Perez Gutierrez 1997).

3.2.2. RADEX analysis

In addition, we have studied the HNCO excitation using RADEX (van der Tak et al. 2007), which is a non-LTE excitation and radiative transfer code that decouples the statistical equilibrium and the radiative transfer equations us-

ing the escape probability method. The calculations assume lines of a given width and rectangular shape. Therefore, the change of the optical depth over the profile is not taken into account. This is not a problem if the opacity of the lines is not very high. We have used the HNCO-H₂ collisional coefficients listed in the LAMDA database (Schöier et al. 2005). The computations use a background temperature of 2.73 K. We have modeled the line fluxes (or integrated intensities) as a function of the hydrogen volume density (n_{H_2}), the HNCO column density (N_{HNCO}), the kinetic temperature (T_K) and the velocity dispersion. The range of hydrogen densities used is 10^3 – 10^6 cm⁻³ and that of N_{HNCO} is 10^{12} – 10^{15} cm⁻². Two kinetic temperatures have been considered: a low kinetic temperature (30 K), only slightly higher than the excitation temperature derived with the HNCO lines and a much higher temperature (250 K), since the actual gas temperature in the shocked gas can be considerably higher than the HNCO excitation temperatures. These temperatures probably cover the different physical conditions of L1157-mm and the shocked sources B1 and B2. We have computed models with velocity dispersions (linewidths) from 1 to 6 km s⁻¹, which cover the measured range of linewidths in the three observed positions. In the range of physical conditions compatible with the observations, the opacity at the peak of the lines is low. Therefore, the predicted integrated intensities are independent of the actual linewidth used to compute the models. For instance, the figures discussed below have been computed with a linewidth of 3 km s⁻¹.

We have based our analysis on the two lowest lines, which are detected towards the three observed positions. Figure 4 shows the model predictions for the 5₀₅–4₀₄ to 4₀₄–3₀₃ line ratio and the 4₀₄–3₀₃ brightness temperature (for a source size of 10'') as a function of n_{H_2} and N_{HNCO} . The same diagrams for a source size equal to the telescope main beam (using T_{mb}) are shown in Fig. 5.

The kinetic temperature cannot be constrained since equally good solutions can be found just changing the hydrogen density by ~ 0.5 dex. For a given source size and kinetic temperature, the H₂ density is similar for B1 and B2. The density varies from 10^4 – $10^{4.4}$ cm⁻³ for a source size of 10'' and $T_K = 250$ K, to $10^{4.6}$ – $10^{5.2}$ cm⁻³ for sources filling the main beam and $T_K = 30$ K. In L1157-mm, n_{H_2} is lower than that in B1 and B2 by 0.2–0.3 dex.

The total HNCO column densities are 0.2–1.3, 0.6–2.5 and 1.3–5.0 (in units of 10^{13} cm⁻²) for mm, B1, and B2, respectively (Table 3). The lower limits are similar to those derived using LTE, while the upper limits for B1 and B2 are somewhat higher because opacity effects start playing a role. Table 3 also shows HNCO abundances computed with the RADEX estimations of the HNCO column density and the total H₂ column density derived from CO by Bachiller & Perez Gutierrez (1997). The HNCO abundances are $(0.3 – 1.2) \times 10^{-9}$ for L1157-mm, $(4.3 – 17.9) \times 10^{-9}$ for L1157-B1 and $(25 – 96) \times 10^{-9}$ for L1157-B2 (Table 3). Therefore, there is a clear increase of the HNCO abundance in the shocked regions, by a factor of 6–14 in B1 and by a factor of 34–83 in B2. *This is the first direct evidence that HNCO is indeed a good tracer of shocked gas.*

In the range of physical conditions and HNCO column densities derived from the 5₀₅–4₀₄ and 4₀₄–3₀₃ lines, the model predictions for the 6₀₆–5₀₅ to 5₀₅–4₀₄ ratio is 0.6–0.7. In contrast, the measured ratio is 0.3–0.4 for L1157-mm,

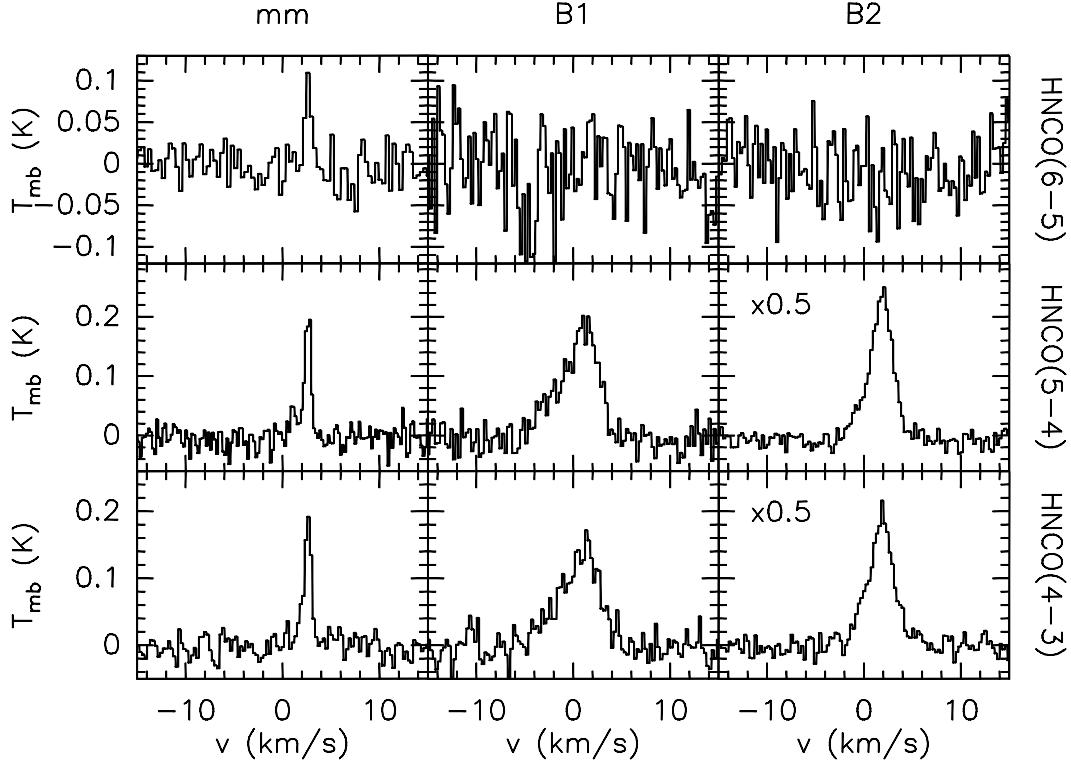


Fig. 2. Observed HNCO spectra. From bottom to top the different panels show the HNCO $4_{04} - 3_{03}$, $5_{05} - 4_{04}$ and $6_{06} - 5_{05}$ spectra towards L1157 mm, B1 and B2.

and it is lower than 0.3 for B1 and B2. As already mentioned above when discussing the LTE analysis, a multi-transition survey would be needed to fully understand the excitation of the molecule. In addition, HNCO maps with high angular resolution will also be needed to determine the positions and the sizes of the different HNCO clumps, in particular to see if there could be some HNCO emission out of the IRAM-30m beam at 2mm.

3.2.3. Comparison with other Galactic sources

Table 4 shows HNCO abundances with respect to H₂ measured other Galactic sources as translucent clouds, photon-dominated regions (PDRs), dense cores and hot cores. The highest HNCO abundance is found in hot cores and dense cores: up to $\sim 8.7 \cdot 10^{-9}$. The HNCO abundance in L1157-mm is similar to that measured in those dense cores and hot cores with the lowest HNCO abundance and in the only “hot corino” where the molecule has been previously detected, IRAS 16293 (van Dishoeck et al. 1995). The HNCO abundance in the L1157-B1 shock is comparable, but can even be higher than that in hot cores and dense cores. Regarding the L1157-B2 shock, the HNCO abundance is at least 4-11 times higher than that in hot cores and dense cores. *The HNCO abundance in the L1157-B2 shock are indeed the highest HNCO abundances ever measured.*

4. Discussion

4.1. HNCO formation in molecular clouds and hot cores

The possible formation pathways of HNCO in shocks have never been modeled. In contrast, HNCO has been included

Table 2. Measured fluxes

Line	mm ^a K km s ⁻¹	B1 ^b K km s ⁻¹	B2 ^c K km s ⁻¹
$4_{0,4} - 3_{0,3}$	0.19	0.71	1.24
$5_{0,5} - 4_{0,4}$	0.19	0.84	1.38
$6_{0,6} - 5_{0,5}$	0.073	< 0.25	< 0.20

Notes. Computed in the velocity range from: ^(a) 1.1 to 3.7 km s⁻¹, ^(b) -4.8 to 5.0 km s⁻¹, ^(c) -2.6 to 6.1 km s⁻¹.

Table 3. Results

Source	T_{ex}^{54a} K	N_{HNCO}^{b} 10^{13} cm^{-2}	N_{HNCO}^{c} 10^{13} cm^{-2}	$X(HNCO)^{d}$ 10^{-9}
mm	8-11	0.2-1.3	0.2-1.3	0.3-1.2
B1	11-19	0.6-2.5	0.6-2.5	4.3-17.9
B2	9-16	1.3-5.0	1.3-5.0	25-96

Notes. ^(a) Excitation temperatures derived from the populations in the $5_{0,5}$ and $4_{0,4}$ levels. ^(b) HNCO column density assuming LTE, optically thin lines and extrapolating using T_{ex}^{54} . ^(c) HNCO column density computed using RADEX. ^(d) HNCO abundance with respect to H₂ (using the H₂ column densities given by Bachiller & Perez Gutierrez 1997)

in some models of dark clouds and hot core chemistry. In the models by Iglesias (1977), HNCO is produced by the ion-neutral reaction $\text{H}_2 + \text{HNCO}^+ \rightarrow \text{H}_2\text{NCO}^+ + \text{H}$ followed by $\text{H}_2\text{NCO}^+ + e^- \rightarrow \text{HNCO} + \text{H}$. Turner et al. (1999) have considered three possible formation pathways, among them the only efficient one is the neutral-neutral reaction

$\text{CN} + \text{O}_2 \rightarrow \text{NCO} + \text{O}$ followed by $\text{NCO} + \text{H}_2 \rightarrow \text{HNCO} + \text{H}$. The last reaction has an activation barrier that has been estimated to be ~ 1160 K by Turner et al. (1999) but that could be as high as 4465 K (Tideswell et al. 2010). In any case, this reaction is not efficient at the typical temperature of a hot core (~ 200 K). Therefore, gas phase chemistry alone cannot explain the HNCO abundances in hot cores. This is also the case for other species as the complex organic molecules. Chemical models have consequently been developed to include reactions on the dust grains surface (Caselli et al. 1993; Garrod et al. 2008; Tideswell et al. 2010). In those works, hot cores are modeled in two stages.

In the first phase, a dark cloud of $n_H \sim 10^4$ cm $^{-3}$ suffers an isothermal collapse. The collapse phase is halted once $n_H \sim 10^7$ cm $^{-3}$, which occurs after approximately $5 \cdot 10^5$ years (free-fall time). The typical temperature at this phase is 10-20 K and surface chemistry is very important then. Surface chemistry models (Garrod et al. 2008; Tideswell et al. 2010) produce HNCO as a secondary radical formed via the reaction $\text{NH} + \text{CO} \rightarrow \text{HNCO}$.² On the grain surface, HNCO can reach a maximum abundance of 10^{-5} (Tideswell et al. 2010) before being destroyed by new reactions with primary radicals (H, CH₃, HCO, NH, ...) giving complex species as HNCHO, HNCOCHO, or CH₃CONH (Garrod et al. 2008).

The cloud-collapse phase is followed by a warm-up phase in which the temperature increases to ~ 200 K. The timescale of the warm-up phase can be as short as $\sim 5 \cdot 10^4$ yr in hot cores but it can reach 10^6 yr in their low mass equivalent (*hot corinos*), giving a similar although slightly different chemistry (Garrod et al. 2008).

During the warm-up phase molecules are evaporated from the grain mantles. With respect to HNCO, the models by Garrod et al. (2008) and Tideswell et al. (2010) show that its abundance increases monotonously with time in the gas phase, which implies that HNCO is not directly ejected from the grains. Instead, HNCO is formed by the destruction in the gas phase of the complex molecules formed from HNCO on the grain surface (Garrod et al. 2008; Tideswell et al. 2010). This mechanism can explain the HNCO abundances measured in hot cores of $10^{-9} - 10^{-8}$. As already mentioned, the contribution of the Turner et al. (1999) and Iglesias (1977) formation pathways is negligible at the moderate temperature of a hot core.

The abundance of HNCO in L1157-mm is similar to that measured in the hot corino of the only other low mass protostar where HNCO has been observed (IRAS16293-2422, see Table 4). Therefore, the HNCO abundance measured in L1157-mm can also be explained in the context of the hot-cores models discussed above. This would imply that L1157-mm can be considered as a hot corino, which is indeed in agreement with the intense emission of water detected by Herschel towards mm (Nisini et al. *in prep*). However, more observations will be needed to clearly establish the hot corino character of L1157-mm, in particular observations of complex organic molecules.

² HNCO formation on the grain surfaces could also occur by reactions of OCN^- with NH_4^+ or H_3O^+ . The inverse reactions (HNCO with NH₃ or H₂O) are invoked to explain the presence of OCN^- ices in the dust grains, (Demyk et al. 1998; van Broekhuizen et al. 2004). To our knowledge, these reactions have never been included in chemical models.

4.2. HNCO formation in shocks

What is the formation pathway of HNCO in the L1157 outflow shocks? The most likely scenario is a combination of grain surface and gas phase chemistry. In the context of shocks, molecules formed on the grain surfaces can be ejected to the gas phase due to grain sputtering instead of thermal evaporation as in hot cores. Therefore, the chemistry will be sensitive to the grain mantles composition at the time of the shock arrival. Currently, there are no models that study the HNCO abundance in dark clouds including grain surface chemistry. Dark clouds models by Tideswell et al. (2010) only consider gas phase reactions. Therefore, the exact grain mantle composition before the arrival of the shock in L1157-B1 and L1157-B2 is not known. Nevertheless, one can compare with the cloud-collapse phase of hot core models (the main difference is that the density during the collapse phase reaches higher values than in dark clouds). As discussed in the previous section, during the collapse phase the HNCO abundance on the grain surfaces has a peak of 10^{-5} , grain sputtering at that time will immediately give rise to very high HNCO abundance in gas phase. Even the very high HNCO abundance in L1157-B2 ($\sim 10^{-7}$) could be accounted for in this context.

On the other hand, gas phase chemistry in shocks differs considerably from that in hot cores because the temperature in the shocked gas can be much higher than that in a hot core. As already pointed out by Zinchenko et al. (2000), in shocks the reaction $\text{NCO} + \text{H}_2$ can be efficient in spite of the activation barrier. In addition, the reaction $\text{CN} + \text{O}_2 \rightarrow \text{NCO} + \text{O}$ will be favored by the high O₂ abundances that are predicted in post-shock gas (Bergin et al. 1998; Gusdorf et al. 2008a,b).³

Using Tideswell et al. (2010) results, it is possible to verify if gas phase chemistry alone could explain the HNCO abundance measured in the L1157 shocks. In one of their dark cloud models (DC1), they have studied the HNCO formation exclusively via the gas phase neutral-neutral reactions of Turner et al. (1999) as a function of the rate coefficient for the reaction $\text{NCO} + \text{H}_2 \rightarrow \text{HNCO} + \text{H}$. Their Fig. 1 shows that a rate coefficient k higher than 10^{-14} cm 3 s $^{-1}$ is needed to explain the observed abundances in L1157 of $10^{-8} - 10^{-7}$. However, to have high HNCO abundance (a few 10^{-8}) *in a short time* (several 10^3 yr) the rate coefficient must be higher than 10^{-12} cm 3 s $^{-1}$. Taking into account the formula $k(T) = 1.5 \cdot 10^{-11} \exp(-4465/T)$ cm 3 s $^{-1}$ given by Tideswell et al. (2010), $k = 10^{-12}$ cm 3 s $^{-1}$ implies a temperature higher than 1600 K. In contrast, the minimum temperature would be 428 K if the activation barrier is only 1160 K (Turner et al. 1999). Gusdorf et al. (2008b) have recently computed shock models to compare the modelled SiO and H₂ emission to observations of L1157. The best agreement between models and observations is found for a preshock density of 10^4 cm $^{-3}$ and a shock speed of 20 km s $^{-1}$. In such a shock, the gas temperature is higher than 430-1600 K for a few thousand years, which is con-

³ This does not mean that the *current* O₂ abundance in the L 1157 shocks is high, but it may have been high just after the passage of a shock-wave as predicted by shock models. Since the chemistry in shocked regions is fast, O₂ can be rapidly converted into other species. Therefore, there is not any contradiction with the fact that the O₂ abundance in the interstellar medium has been found to be low ($< 10^{-7}$ Larsson et al. 2007).

Table 4. HNCO abundance with respect to H₂ in different astronomical environments.

Source	X(HNCO) 10 ⁻⁹	References
L1157-B2	25-96	1
Translucent clouds	0.2-5	2
Orion bar PDR	< 10 ⁻²	3
Dense cores	0.2-8.7	4
Orion Hot core	5	5
SgrB2M	1	6
W3(H ₂ O)	5.0-27	7
G34.3+0.15	1.4	8
IRAS 16293	0.17-4.0	9, 10
GC clouds	3-48	11,12
Starburst galaxies	1-6.3	13

References. (1) This work; (2) Turner et al. (1999); (3) Jansen et al. (1995); (4) Zinchenko et al. (2000); (5) Blake et al. (1987); (6) Minh et al. (1998); (7) Helmich & van Dishoeck (1997); (8) Bockelée-Morvan et al. (2000), using the HNCO column density given by MacDonald et al. (1996) and the H₂ column density given by Hatchell et al. (1998); (9) van Dishoeck et al. (1995); (10) Bisschop et al. (2008); (11) Rizzo et al. (2000); (12) Martín et al. (2008), and references within; (13) Martín et al. (2009)

sistent with the dynamical age of the B1 and B2 shocks (2000-3000 yr, Gueth et al. 1998) and with the chemical time necessary to have an HNCO abundance of a few 10⁻⁸ only with gas phase reactions (Figure 1 of Tideswell et al. 2010). Therefore, gas phase chemistry alone could explain the HNCO abundance in L1157-B1. However, it is unclear whether a HNCO abundance as high as that measured in L1157-B2 ($\sim 10^{-7}$) can be attained in a few thousand years only with gas phase reactions.

Therefore, we reckon that the most likely explanation to the high HNCO abundances in L1157 is dust grain mantles processing by the shock waves followed by neutral-neutral reactions in gas phase.

4.3. Chemical differences between B1 and B2 and the role of the O₂ chemistry

We have discussed the line profiles and the line intensities of different species in Sect. 3.1. The HNCO profiles are very similar to those of SO and SO₂. In addition, the lines of most of the molecules show similar intensities in B1 and B2 with the exception of CN, which is more intense in B1, and HNCO, SO₂ and OCS, whose lines are more intense emission in B2 than in B1. These similarities of HNCO and the sulfured molecules is somewhat puzzling.

The actual reason of the chemical differences in B1 and B2 is not clear. The present gas density in B1 and B2 is similar (see Figs. 4 and 5 and Bachiller & Perez Gutierrez 1997; Nisini et al. 2007). In contrast, based on the line profiles, the shock velocity can be higher in B1 than in B2. Taking into account the extreme SiO line wings, the difference could reach 10 km s⁻¹, which after the Gusdorf et al. (2008a) models could be significant.

Alternatively, Bachiller & Perez Gutierrez (1997) have suggested that the chemical differences between B1 and B2 could be due to different shock ages. Indeed, in contrast to SO₂ and OCS, the H₂S abundance is lower in

B2 than in B1. This is consistent since H₂S is a parent molecule for other sulfured species. H₂S is formed in the grain surfaces and released to the gas phase by effect of the shock waves. Other sulfur-bearing molecules like SO and SO₂ are produced in gas phase very quickly (few 10³ yr) via reactions with H, OH and O₂ (Pineau des Forêts et al. 1993; Wakelam et al. 2005). One possible explanation of the differences in B1 and B2 is that the B2 shock could be older than that in B1 and that H₂S has been converted into SO and SO₂. Even if there are uncertainties regarding the sulfur chemistry (see for instance Codella et al. 2005, and references therein), sulfur-bearing molecules like H₂S, SO, SO₂, H₂CS and OCS have been invoked to be potential valuable probes of chemical evolution (Codella et al. 2005; Wakelam et al. 2005; Herpin et al. 2009). In particular, Wakelam et al. (2005) have found that the SO₂/SO ratio increases with the shock age. The higher SO₂/SO ratio in B2 compared to B1 also points to an older shock in B2. Bachiller & Perez Gutierrez (1997) have also proposed that the different CN abundance in B1 and B2 can be accounted for in this scenario of an older shock in B2, since after an enhancement of CN in the shock, reactions like CN+O \rightarrow CO+N could be very efficient to destroy CN. Our data globally agree with this scenario, nevertheless the clear anticorrelation of the CN and HNCO intensities and the similar abundances of CN and HNCO in L1157-B1 suggest that *all* the CN can indeed be transformed into HNCO once the shock has increased the temperature and the neutral-neutral reactions form NCO from CN and O₂ and HNCO from NCO (see Sect. 4.2). Therefore, the chemical differences from B1 and B2 do support the scenario proposed in Sect. 4.2 to explain the HNCO abundances in the L1157 shocks.

In addition, the scheme proposed in Sect. 4.2 also gives insight on the possible link of HNCO and the sulfured molecules, in particular with SO and SO₂. In shocks these molecules can be produced by the reactions S + O₂ \rightarrow SO + O and SO + OH \rightarrow SO₂ + OH (Pineau des Forêts et al. 1993; Charnley 1997; Wakelam et al. 2005). Therefore, the common link with HNCO would be formation pathways involving O₂.

Another important shock tracer that could be linked to the O₂ chemistry is SiO. Nevertheless, the situation regarding this molecule is more complex. First, recent models can explain the SiO emission in shocks without a significant contribution of Si oxidation in gas phase, either by sputtering in gas-grain collisions if there is already SiO in the grain mantles (Gusdorf et al. 2008b) or by dust vaporization in grain-grain collisions (Guillet et al. 2009). Second, if one assumes that SiO is formed in gas phase, there is a threshold shock velocity of ~ 25 km s⁻¹ in order to eject Si from the grain cores by sputtering (Gusdorf et al. 2008a). In contrast, other molecules as the organics are in the grain mantles and there is not such a high velocity threshold for them to be ejected to gas phase. Therefore, both if SiO comes directly from the grains (Gusdorf et al. 2008b; Guillet et al. 2009) or if it is formed in gas phase (Gusdorf et al. 2008a), due to the shock velocity threshold, it is not expected to find similarities (and not observed) in the SiO emission and that of SO, SO₂ and HNCO.

It is interesting to note that the impressive SiO blue wing in B1 (Bachiller & Perez Gutierrez 1997) suggests that SiO formation is indeed favored, in comparison to other molecules, in the higher velocity gas. In this con-

text, chemical differences in B1 and B2 could also be due to different shock velocities. If the shock velocity in B2 is actually lower than in B1 and the SiO formation less efficient, more O₂ will remain available in B2 to form HNCO, SO and SO₂.

4.4. On the origin of the HNCO emission in galactic nuclei

The HNCO abundance in the molecular clouds in the center of the Milky Way and in the nuclei of starburst galaxies is similar or a bit higher (at most by a factor of 2) than in Galactic hot cores (Table 4). HNCO becomes another piece in the well known puzzle of the chemistry of the Galactic center molecular clouds. This puzzle can be summarized as follows: the abundance of SiO and complex organic molecules in the Galactic center is as high as in hot cores (Martín-Pintado et al. 1997; Rodriguez-Fernandez et al. 2006; Requena-Torres et al. 2006). In contrast, (i) the emission in the Galactic center is extended over the central 300 pc and it does not resemble a collection of discrete sources with the size of a hot core (~ 0.1 pc), (ii) the gas density ($10^3 - 10^4$ cm⁻³) is much lower than in hot cores (iii) and the dust temperatures (< 30 K) are also much lower than in hot cores. The Galactic center clouds present a “hot core chemistry without hot cores” (Requena-Torres et al. 2006). The origin of this chemistry is not known although it is thought to be due to some type of mechanical processes as shock waves (Martín-Pintado et al. 1997, 2001; Rodriguez-Fernández et al. 2004). The origin of the shocks can be related to the complex dynamics in the inner regions of the Galaxy (Hüttemeister et al. 1998; Rodriguez-Fernandez et al. 2006; Rodriguez-Fernandez & Combes 2008).

Based on the spatial distribution of the HNCO and the comparison with other species, as CH₃OH, Meier & Turner (2005) have also suggested that the HNCO emission in IC342 is tracing shocks. Recently, Martín et al. (2008, 2009) have also proposed that shocks could be the explanation of the high HNCO abundances measured in galactic nuclei.

Discussing the precise origin of shocks in Galactic nuclei is out of the scope of this paper. Nevertheless, our observations support the scenario of HNCO tracing shocks in galactic nuclei since our L1157 results probe a medium of moderate H₂ density where the HNCO abundance is indeed high due to the grain processing and gas heating by shock waves.

5. Summary

We have observed three lines of HNCO towards the protostar L1157 and its associated molecular outflow. Our aim is to characterize the HNCO properties in shocked gas. HNCO is well detected in the shocked gas, where the abundance increases by a factor of 6-34 with respect to the abundance in the protostar L1157-mm. The abundance in B1 and B2 is 0.4-1.8 10⁻⁸ and 0.3-1 10⁻⁷, respectively. The abundance in B2 is the highest ever measured, considerably higher than those in hot cores (a few 10⁻⁹) and galactic nuclei (10⁻⁹ – 10⁻⁸). Our results probe that the HNCO abundances measured in galactic nuclei can easily be attained in shocked gas, providing a solid basis to previous suggestions

that the extended HNCO in galactic nuclei could trace large scale shocks (Meier & Turner 2005; Minh & Irvine 2006).

The dominant formation pathway of HNCO in hot cores is grain mantle evaporation of complex molecules formed from HNCO and subsequent dissociation to give again HNCO. In addition, there is contribution from gas phase reactions, but it is minor due to the high activation barriers of some reactions (Tideswell et al. 2010). In the L1157 shocks we propose a relatively similar formation pathway although with different relative importance of the dust surface and gas phase chemistry. First there should be grain mantles erosion by the shock waves that will increase the HNCO abundance in gas phase. Second, in contrast to hot cores, the neutral-neutral reactions in gas phase can be the dominant formation pathway due to the higher gas temperatures in the shocked gas with respect to the typical temperature of hot cores. These reactions start with the formation of OCN from CN and O₂, which is expected to be very abundant in gas phase in a magneto-hydrodynamic shock of relatively low velocity (20-30 km s⁻¹) like the L1157 shocks (Gusdorf et al. 2008a). The observed anticorrelation of CN and HNCO fluxes also support this scenario.

HNCO line profiles are very similar to those of CH₃OH and H₂CO lines, which is not surprising since all those molecules have, at least partially, a common origin linked to the grain surface chemistry and subsequent desorption. In addition, HNCO line profiles are also similar to some sulfur-bearing molecules like SO and SO₂. Another common property of HNCO and the sulfur-bearing molecules is that they are the only species that exhibit a more intense emission in B2 than B1. We propose that the common link of HNCO and the sulfured molecules is that in both cases there are formation pathways with reactions involving O₂. HNCO together with the sulfured molecules are good probes of chemical differentiation in shocks. In particular, in the case of L1157 the highest abundances in B2 than in B1 could be due to a lower shock velocity and/or an older shock in B2 than in B1.

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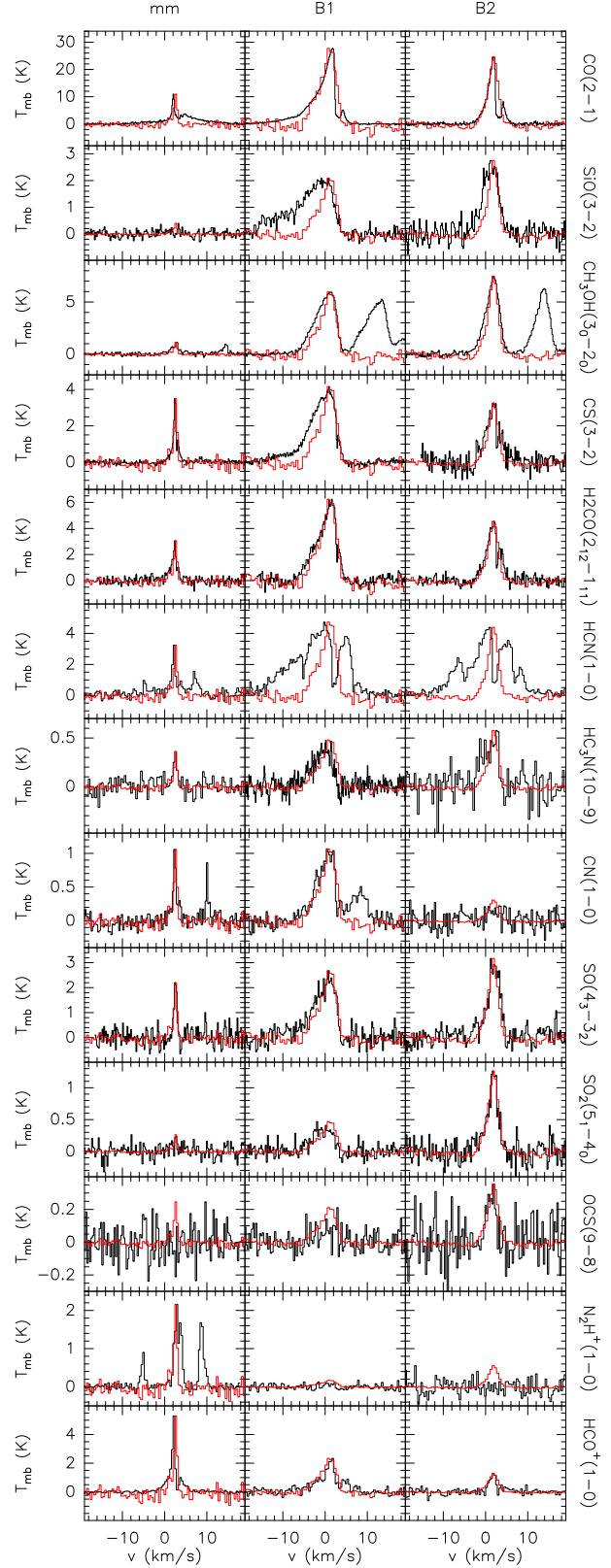


Fig. 3. Comparison of the HNCO(505 – 404) line profiles (in red) with the spectra of other species published by Bachiller & Perez-Gutierrez (1997), in black lines. The HNCO peak temperature has been scaled to the peak temperature of the other molecule in order to compare profiles.

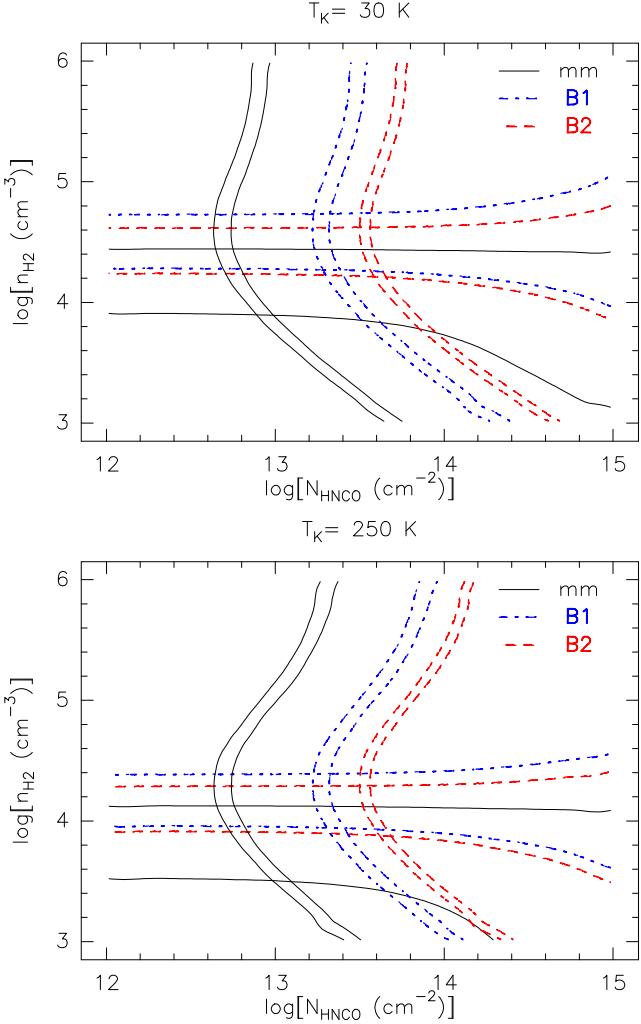


Fig. 4. RADEX results for the $505 - 404$ to $404 - 303$ flux ratio (horizontal curves) and the $404 - 303$ line flux (vertical curves) computed with a brightness temperature for a source size of $10''$ as a function of the hydrogen density, the HNCO column density and the kinetic temperature (30 K in the upper panel and 250 K in the lower panel). A typical uncertainty of 10 % in the line flux has been taken into account.

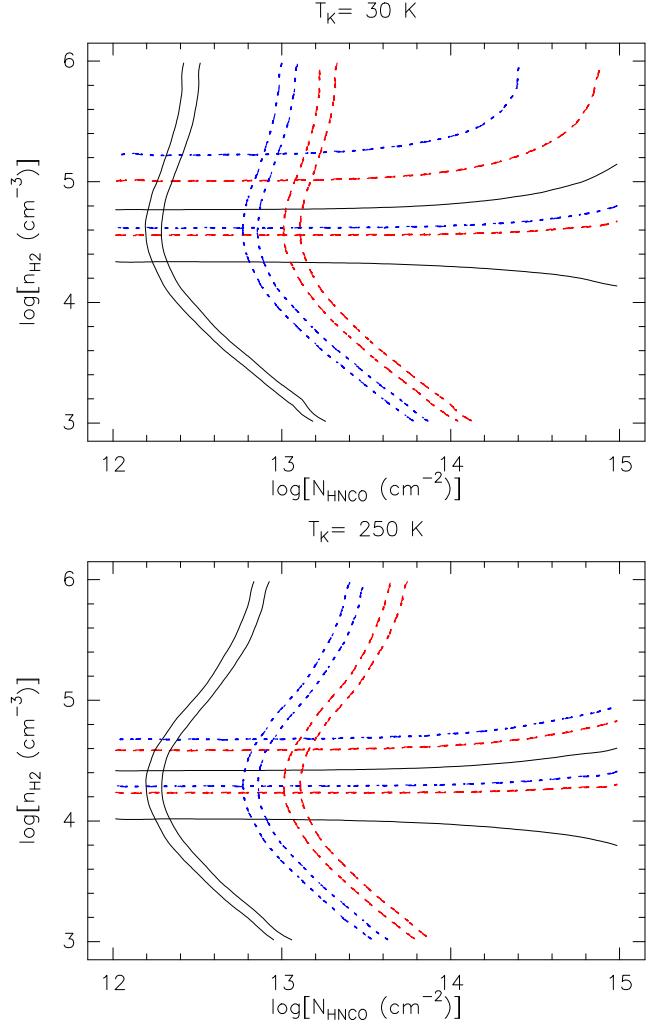


Fig. 5. Same than Fig. 4 but using T_{mb} .